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**PROJECTION OPTICAL SYSTEM AND EXPOSURE APPARATUS AND METHOD****Field of the Invention**

The present invention relates to projection optical systems and exposure apparatus

- 5 incorporating same and methods pertaining to same, and in particular to such systems, apparatus and methods for manufacturing devices and elements, such as integrated circuits, liquid crystal displays, detectors, MR (magneto-resistive) heads, and the like.

**Background of the Invention**

- 10 Step-and-repeat and step-and-scan projection exposure apparatus are presently used to manufacture semiconductor devices and the like. In step and repeat projection exposure apparatus ("steppers"), each exposure field is exposed in a single static exposure. In step-and-scan projection exposure apparatus ("scanners"), each exposure field is scanned during exposure. A projection exposure apparatus as used in semiconductor manufacturing, for
- 15 example, transfers an image of a pattern on a reticle, which is used as a mask, through a projection optical system and onto a wafer (or glass plate or like workpiece) coated with a photo-sensitive medium, such as photoresist. With the increasing miniaturization of the patterns of semiconductor integrated circuits and other similar devices, there is an increasing demand to increase the resolving power of projection optical systems incorporated into
- 20 projection exposure apparatus. The resolving power of the projection optical system can be increased by either shortening the exposure wavelength or increasing the image-side numerical aperture (NA).

- The wavelengths used in projection exposure apparatus for semiconductor manufacturing are
- 25 principally mercury lamp g-line ( $\lambda = 436 \text{ nm}$ ) to the i-line ( $\lambda = 365 \text{ nm}$ ). More recently, efforts are being made to employ shorter wavelength light sources, for example excimer lasers ( $\lambda = 248 \text{ nm}$ ,  $193 \text{ nm}$ ). Consequently, projection optical systems are being developed that have optical characteristics that can be used with exposure light of short wavelength.

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In addition, the demand for both increased resolving power and reduced image distortion in projection optical systems has increased. Image distortion as a whole includes several contributing factors, such as distortion inherent in the projection optical system, distortion due to warping of the wafer upon which the circuit pattern is printed, and distortion due to warping of the reticle on which the circuit pattern to be imaged resides.

To reduce the effect of image distortion due to warping of the wafer, imagewise telecentric projection optical systems have been developed. In such systems, the exit pupil is located at infinity objectwise of the projection optical system. Likewise, to reduce image distortion due to warpage of the reticle, objectwise telecentric optical systems have been employed, wherein the entrance pupil of the projection optical system is located at infinity imagewise of the projection optical system. Such projection optical systems are disclosed in, for example, Japanese Patent Application Kokai No. Sho 63-118115, United States patent No. 5,260,832 and Japanese Patent Application Kokai No. Hei 5-173065.

In addition, there have been demands for being able to select and adjust the NA to be more ideally suited for printing particular types of patterns on the reticle, as well as to account for other manufacturing conditions. In particular, there have been demands for the projection optical systems in exposure apparatus to have a variable aperture stop whose size can be varied to change the NA of the projection optical system.

Also, if a plurality of lens surfaces in the projection optical system are made aspherical, it is possible to reduce the number of lenses used. Examples of such projection optical systems are disclosed in, for example, United States Patent No. 4,928,238, Japanese Patent Application Kokai No. Hei 5-34593 and Japanese Patent Application Kokai No. Hei 7-128592.

As described above, it is desirable to make the projection optical system both imagewise and objectwise telecentric (i.e., "double-telecentric") to reduce the effects of both wafer warping and reticle warping on image distortion. Therefore, as disclosed in the abovementioned patent applications, projection optical systems have been developed that are double-

telecentric. Nevertheless, in prior art double-telecentric projection optical systems, it has proven difficult to make the NA sufficiently large while simultaneously reducing the various aberrations over a large exposure field. In particular, in the prior art systems, distortion correction is generally inadequate.

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Moreover, in the prior art projection optical systems, if a variable aperture stop is provided to vary the NA of the projection optical system, vignetting occurs at the periphery of the exposure field due to spherical aberration at the pupil when the aperture stop size is changed. Consequently, uniformity of illumination suffers in the exposure field periphery. In addition, telecentricity degrades when the numerical aperture is varied, and there is also the problem that the exposure field size cannot be increased.

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Furthermore, the projection optical systems with aspherical surfaces disclosed in the abovementioned patent applications introduce aspherical surfaces for the purpose of reducing the overall glass thickness of the optical system and of improving transmittance. However, this has not lead to projection optical systems having large exposure regions and a sufficiently large numerical apertures.

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### **Summary of the Invention**

The present invention relates to projection optical systems and exposure apparatus incorporating same and methods pertaining to same, and in particular to such systems, apparatus and methods for manufacturing devices and elements, such as integrated circuits, liquid crystal displays, CCD (charge coupled device) detectors, MR (magneto-resistive) heads, and the like.

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The present invention takes the above problems into consideration and has several objectives. The first objective is to provide a compact high-performance projection optical system that is double-telecentric, and that includes an aperture stop capable of reducing the effects of vignetting when the numerical aperture (NA) is varied. A second objective is a projection optical system that is extremely well-corrected for the various aberrations, particularly distortion, while ensuring, through the use of aspherical lens surfaces, a sufficiently large

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numerical aperture and a large exposure field. A third objective to provide an exposure apparatus which includes with the abovementioned projection optical system, and a semiconductor device manufacturing method employing the exposure apparatus.

- 5 Accordingly, a first aspect of the present invention is a projection optical system capable of forming an image of an object. The system comprises, objectwise to imagewise, along an optical axis, a first lens group having positive refractive power, a second lens group having negative refractive power, a third lens group having positive refractive power, a fourth lens group having negative refractive power and a first aspherical surface, and a fifth lens group
- 10 having positive refractive power and an aperture. The projection optical system is designed such that paraxial rays traveling parallel to the optical axis imagewise to objectwise intersect the optical axis at a location Q between the fourth lens group and the fifth lens group. Further, at least one of the fourth and fifth lens groups includes a second aspherical surface arranged between the first aspherical surface in the fourth lens group and the aperture stop.
- 15 Also, the fifth lens group includes a third aspherical surface arranged imagewise of the aperture stop. In addition, the following condition is satisfied:

$$0.01 < d_Q / \{L \times (1 - NA)\} < 0.4 \quad (1)$$

- 20 wherein the image and the object are separated by a distance L, the location Q and the aperture stop are separated by a distance  $d_Q$ , and NA is an imagewise numerical aperture of the projection optical system.

- A second aspect of the present invention is a projection optical system as described above,
- 25 wherein the aperture stop has a variable size and is located imagewise of the location Q such that vignetting is minimized when the variable size is changed.

A third aspect of the invention is a projection optical system as described above, which satisfies the following conditions:

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$$0.05 < f_1/L < 0.5 \quad (2)$$

$$0.02 < -f_2/L < 0.2 \quad (3)$$

$$0.04 < f_3/L < 0.4 \quad (4)$$

$$0.03 < -f_4/L < 0.3 \quad (5)$$

$$0.04 < f_5/L < 0.4 \quad (6)$$

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wherein  $f_1$  through  $f_5$  are focal lengths of the first through fifth lens groups, respectively.

A fourth aspect of the present invention is an exposure apparatus for imaging a pattern present on a reticle onto a photosensitive workpiece. The apparatus comprises a reticle stage  
10 for supporting the reticle, an illumination optical system adjacent the reticle stage for illuminating the reticle, a workpiece stage for supporting a workpiece, and the projection optical system as described above arranged between the reticle stage and the workpiece stage.

A fifth aspect of the present invention is a method of patterning a photosensitive workpiece  
15 with a pattern present on a reticle. The method comprises the steps of first illuminating the reticle, then projecting light from the reticle with the projection optical system as described above, and then exposing the photosensitive workpiece over an exposure field.

A sixth aspect of the present invention is a device manufacturing method comprising the  
20 steps of first coating a photosensitive material onto a substrate, then projecting onto the substrate the image of a pattern of reticle through the projection optical system as described above, then developing the photosensitive material on the substrate, thereby forming a photoresist pattern.

## 25 **Brief Description of the Drawings**

FIG. 1 is a schematic optical diagram of the projection exposure apparatus of the present invention;

FIG. 2 is an optical diagram of the projection optical system of Working Example 1 of the  
30 present invention;

FIGS. 3A-3D are aberration plots for spherical aberration, astigmatism, distortion, and coma, respectively, for the projection optical system of FIG. 2;

FIG. 4 is an optical diagram of the projection optical system of Working Example 2 of the  
5 present invention;

FIGS. 5A-5D are aberration plots for spherical aberration, astigmatism, distortion, and coma, respectively, for the projection optical system of FIG. 4;

10 FIG. 6 is an optical diagram of the projection optical system of Working Example 3 of the present invention;

FIGS. 7A-7D are aberration plots for spherical aberration, astigmatism, distortion, and coma, respectively, for the projection optical system of FIG. 6;

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FIG. 8 is an optical diagram of the projection optical system of Working Example 4 of the present invention;

FIGS. 9A-9D are aberration plots for spherical aberration, astigmatism, distortion, and coma, respectively, for the projection optical system of FIG. 8; and

FIG. 10 is a flowchart of a preferred method of manufacturing a semiconductor device patterning a wafer with the exposure apparatus and projection optical system of the present invention.

## Detailed Description of the Invention

The present invention relates to projection optical systems and exposure apparatus incorporating same and methods pertaining to same, and in particular to such systems, apparatus and methods for manufacturing devices and elements, such as integrated circuits, liquid crystal displays, CCD (charge coupled device) detectors, MR (magneto-resistive) heads, and the like.

With reference to FIG. 1, exposure apparatus 10 includes a projection optical system PL having an object plane 12, an image plane 14, and an aperture stop AS disposed along an optical axis A. Projection optical system PL is substantially double-telecentric. Aperture stop AS is variable and disposed in the vicinity of the pupil position. An object, such as a reticle R, is disposed at or near object plane 12. Object (mask, reticle, or original) R is typically a transparent substrate, such as fused silica, and includes a pattern (not shown) having small (i.e., micron and sub-micron) features. Object (reticle) R is held in place and moved into a position at or near object plane 12 by object (reticle) stage RS. Disposed adjacent object (reticle) R along optical axis A opposite projection lens PL is an illumination optical system IS. The latter includes an exposure light source (not shown) for generating a light beam L.

Examples of exposure light sources are: a KrF excimer laser emitting light at a wavelength of 248.4 nm, an ArF laser emitting light at a wavelength of 193 nm, a F<sub>2</sub> laser emitting light at a wavelength of 157 nm, the higher harmonics of a solid state laser (e.g. a YAG laser) emitting light at a wavelength of e.g. 248 nm, 193 nm, or 157 nm, or the various lines of a mercury arc lamp emitting a wavelength of, e.g., g-line, h-line, or i-line, mentioned above. Moreover, wavelengths associated with the higher harmonics converted from monochromatic laser light emitted from a DFB (distributed feedback) semiconductor laser or fiber laser into ultraviolet light by a nonlinear optical crystal may be employed. For example, when the range of wavelengths of the monochromatic laser are set at 1.51 to 1.59 microns, eighth-order harmonics having a wavelength range from 189 nm to 199 nm can be obtained. Likewise, tenth-order harmonics having wavelength range 151 nm to 159 nm can also be obtained. In particular, when the wavelength range of the monochromatic laser are set at 1.544 to 1.553 microns, wavelengths in the range from 193 nm to 194 nm can be obtained (i.e., the same wavelengths as from an ArF excimer laser). When the wavelength range of the monochromatic laser is set at 1.57 to 1.58 microns, tenth-order harmonics having a wavelength range from 157 nm to 158 nm can be obtained (i.e., the same as from an F<sub>2</sub> laser).

Illumination optical system IS is designed to uniformly illuminate reticle R and also to form a source image at aperture stop AS in the absence of pattern of object (reticle) R (i.e., Kohler

illumination). A workpiece W, such as a silicon wafer coated with photoresist, is disposed along optical axis A at or near image plane 14. Workpiece (wafer) W is held in place and moved into position by a workpiece (wafer) stage WS.

5 Generally speaking, to pattern workpiece (wafer) W with exposure apparatus 10, object (reticle) R and workpiece (wafer) W are moved into proper alignment using object (reticle) stage RS and workpiece (wafer) stage WS, respectively. Object (reticle) R is then illuminated with illumination optical system IS for a certain amount of time. An image of the pattern on object (reticle) R is projected onto workpiece (wafer) W over an exposure field EF, via  
10 projection lens PL. Workpiece (wafer) stage WS then moves an incremental amount and another exposure is made on workpiece (wafer) W. The process is repeated until a desired area of workpiece (wafer) W is exposed. Exposure apparatus 10 and methods associated therewith are discussed in further detail below.

15 In a preferred embodiment, reticle stage RS and workpiece (wafer) stage WS are moveable along a scanning direction (e.g., the X-direction), and exposure field EF has a first dimension orthogonal to the scanning direction (e.g., the Y-direction) and a second dimension in the scanning direction. Preferably, the first dimension is greater than the second dimension. Also, in a preferred embodiment, the first dimension is approximately at least 25 mm. In the  
20 case where a stitching exposure is used, it is preferable that the first dimension be approximately at least 15mm when the exposure field EF has a trapezoid shape, hexangular shape, parallelogram shape, diamond shape, or other such polygonal shape. Such stitching exposure methods are disclosed in United States Patents No. 5,437,946, 5,477,304, and 5,617,182.

### 25 **Projection Optical System**

With reference now to FIG. 2, the projection optical system of the present invention is described with reference to projection optical system 20 representing a Working Example 1 of the present invention. Projection optical system 20 comprises, in order from reticle R (i.e.,  
30 object plane OP) to workpiece (wafer) W (i.e., image plane IP), or "objectwise to imagewise," a first lens group G1 having positive refractive power, a second lens group G2



having negative refractive power, a third lens group G3 having positive refractive power, a fourth lens group G4 having negative refractive power, and a fifth lens group G5 having positive refractive power.

- 5 Projection optical system 20 is double-telecentric and designed to operate at a particular exposure wavelength or a narrow band centered thereon (e.g.,  $\lambda = 248.4$  nm). A location Q wherein paraxial rays traveling parallel to optical axis A imagewise to objectwise intersect the optical axis is located between fourth lens group G4 and fifth lens group G5. A variable aperture stop AS for setting the NA is arranged imagewise of location Q in lens group G5.
- 10 As a result of this configuration, the difference in vignetting over the entire surface of the exposure field EF on workpiece (wafer) W (FIG. 1) is minimized.

With continuing reference to FIG. 2 and projection optical system 20, first lens group G1 contributes principally to the correction of distortion while maintaining telecentricity.

- 15 Second lens group G2 and fourth lens group G4 contribute principally to the correction of the Petzval sum and have the function of flattening image plane IP. Third lens group G3 generates positive distortion together with first lens group G1, and serves to correct negative distortion generated by second lens group G2, fourth lens group G4 and fifth lens group G5. Third lens group G3 and second lens group G2 constitute a telephoto system having a
- 20 positive-negative refractive power arrangement when viewed imagewise to objectwise. This combination prevents enlargement of projection optical system 20. To cope with the increased imagewise NA, fifth lens group G5 suppresses the generation of distortion particularly in the state wherein the generation of spherical aberration is minimized, guides the light beam onto workpiece (wafer) W, and serves the role of forming an image.

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It is also preferable that the projection optical system of the present invention satisfy at least one of a number of design conditions set forth below.

- The first condition (1) stipulates the requirements for facilitating double-telecentricity, as
- 30 well as for reducing the effects of vignetting in the exposure field. Condition (1) is expressed as

$$0.01 < d_Q / \{L \times (1 - NA)\} < 0.4 \quad (1)$$

wherein L is the distance from object plane OP to image plane IP, NA is the imagewise numerical aperture, and  $d_Q$  is the axial distance from location Q to aperture stop AS (positive when measured from location Q imagewise).

If  $d_Q / \{L \times (1 - NA)\}$  exceeds the upper limit in condition (1) pupil aberration increases excessively and it is difficult to obtain double-telecentricity. Conversely, if  $d_Q / \{L \times (1 - NA)\}$  falls below the lower limit in condition (1), overcorrection of pupil aberration results as the Petzval sum approaches zero, which enlarges the projection optical system.

It is also preferable in the projection optical system of the present invention that variable aperture stop AS be arranged imagewise of location Q. This minimizes the difference in vignetting over the exposure field when the NA is changed by varying the size of aperture stop AS. With continuing reference to FIG. 2, the advantage of this configuration can be understood by considering a parallel light beam (not shown) entering projection optical system 20 imagewise to objectwise. The paraxial principle rays of this beam intersect optical axis A at location Q, due to refraction of the positive lenses imagewise of location Q. Since these positive lenses have positive refractive power, a parallel light beam impinging thereon at a predetermined angle with respect to optical axis A forms an image at a position imagewise from location Q. Accordingly, if aperture stop AS is located imagewise of location Q, the effect of vignetting at the periphery of the exposure field due to the field curvature of the pupil can, for practical purposes, be adequately controlled. Also, the various aberrations can be satisfactorily corrected, even if the size of aperture stop AS is varied.

The second design condition stipulates the optimal refractive power range for first lens group G1 and is expressed as:

$$0.05 < f_1 / L < 0.5 \quad (2)$$

wherein  $f_1$  is the focal length of first lens group G1. If  $f_1/L$  exceeds the upper limit in condition (2), positive distortion generated by first lens group G1 cannot be fully corrected by the negative distortion generated by second, fourth and fifth lens groups G2, G4 and G5. Conversely, if  $f_1/L$  falls below the lower limit in condition (2), high-order positive distortion is generated.

A third design condition stipulates the optimal refractive power range for second lens group G2 and is expressed as:

$$0.02 < -f_2/L < 0.2 \quad (3)$$

wherein  $f_2$  is the focal length of second lens group G2. If  $-f_2/L$  exceeds the upper limit in condition (3), the correction of the Petzval sum is not sufficiently corrected, making it difficult to flatten the image plane. Conversely, if  $-f_2/L$  falls below the lower limit in condition (3), the generation of negative distortion increases, and it becomes difficult to satisfactorily correct such a large negative distortion by just first and third lens groups G1 and G3.

A fourth design condition stipulates the optimal refractive power range for third lens group G3 and is expressed as:

$$0.04 < f_3/L < 0.4 \quad (4)$$

wherein  $f_3$  is the focal length of third lens group G3. If  $f_3/L$  exceeds the upper limit in condition (4), the projection optical system increases in size, since the telephoto ratio of the telephoto system formed by second lens group G2 and third lens group G3 increases. In addition, positive distortion generated by third lens group G3 decreases, and negative distortion generated by second, fourth and fifth lens groups G2, G4 and G5 can no longer be satisfactorily corrected. Conversely, if  $f_3/L$  falls below the lower limit in condition (4), satisfactory imaging performance can no longer be obtained due to the generation of high-order spherical aberration.

A fifth design condition stipulates the optimal refractive power range for fourth lens group G4 and is expressed as:

$$0.03 < -f4/L < 0.3 \quad (5)$$

wherein f4 is the focal length of fourth lens group G4. If -f4/L exceeds the upper limit in condition (5), the Petzval sum not sufficiently corrected, making it difficult to achieve a flat image plane. Conversely, if -f4/L falls below the lower limit in condition (5), high-order spherical aberration and coma is generated.

A sixth design condition stipulates the optimal refractive power of fifth lens group G5 is expressed as:

$$0.04 < f5/L < 0.4 \quad (6)$$

wherein f5 is the focal length of fifth lens group G5. If f5/L exceeds the upper limit in condition (6), the overall refractive power of fifth lens group G5 is excessively weak, which enlarges the projection optical system. Conversely, if f5/L falls below the lower limit in condition (6), high-order spherical aberration is generated and image contrast deteriorates.

In addition to satisfying at least one of the above design conditions, it is also preferable that the projection optical system of the present invention have one or more aspherical surfaces, each having a paraxial (i.e., near-axis) region, a periphery (i.e., the portion of the surface farthest from the axis), and refractive power.

With continuing reference to projection optical system 20 of FIG. 2, in a first preferred embodiment, fourth lens group G4 has at least one aspherical surface ASP1, and fourth or fifth lens group G4 or G5 has at least one aspherical surface ASP2 arranged between aspherical surface ASP1 and aperture stop AS. In addition, fifth lens group G5 has at least one aspherical surface ASP3 arranged imagewise of aperture stop AS.





surfaces (Tables 1B- 4B), and values for the parameters and design conditions of Working Examples 1-4 (Tables 1C- 4C). In Tables 1A- 4A, D0 is the axial distance from object (reticle) R to the most objectwise lens surface of first lens group G1, WD is the axial distance (working distance) from the most imagewise lens surface of fifth lens group G5 to workpiece (wafer) W,  $\beta$  is the projection magnification of the projection optical system, NA is the image-side numerical aperture of the projection optical system,  $d_{EX}$  is the diameter of exposure field EF on workpiece (wafer) W (see FIG. 1), and L is the axial distance between the object (reticle) R (i.e., object plane OP) and workpiece (wafer) W (i.e., image plane IP). In Tables 1A-4A, S is the surface number of the optical components arranged objectwise to imagewise, r is the radius of curvature of the corresponding lens surface, d is the axial distance between adjacent lens surfaces, n is the refractive index of the glass at wavelength  $\lambda = 248.4$  nm. Silica glass, for example, can be used as the glass material. The unit of measurement of the radius of curvature r and the axial distance d is millimeters, for example.

Also, in Tables 1B-4B, "E" denotes "exponential" such that "En" means "10<sup>n</sup>".

The expression for an aspherical surface is as follows:

$$Z = \{ch^2/(1 + \sqrt{1 - (1 + \kappa)c^2h^2})\} + Ah^4 + Bh^6 + Ch^8 + Dh^{10} + Eh^{12} + Fh^{14}$$

wherein Z is the amount of sag of a surface parallel to the optical axis, c is the curvature at the apex of the surface, h is the distance from the optical axis, and  $\kappa$  is the conical coefficient.

The letters A, B, C, D, E, F are aspherical surface coefficients.

In the Working Examples below, if the maximum value of the NA = NA<sub>MAX</sub> = 0.8 and the variable range of the NA is set to approximately 60% of the maximum value, then the variable range of NA due to varying the size of aperture stop AS becomes approximately  $0.5 \leq NA \leq 0.8$  (i.e.,  $0.6 \times NA_{MAX} \leq NA \leq NA_{MAX}$ ).

FIGS. 3A-3D, 5A-5D, 7A-7D and 9A-9D are aberration plots for spherical aberration (3A-9A), astigmatism (3B-9B), distortion (3C-9C) and coma (tangential and sagittal) (3D-9D) for Working Examples 1-4, respectively. In each aberration plot, Y is the image height. In the astigmatism plots (3B-9B), the broken line represents the tangential image plane and the solid line represents the sagittal image plane.

#### Working Example 1

With reference to FIG. 2, projection optical system 20 represents Working Example 1 of the present invention. Projection optical system 20 is double-telecentric and comprises,

objectwise to imagewise, as described above, a first lens group G1 having positive refractive power, a second lens group G2 having negative refractive power, a third lens group G3 having positive refractive power, a fourth lens group G4 having negative refractive power, and a fifth lens group G5 having positive refractive power. Projection optical system 20 is double-telecentric. Location Q is located between fourth lens group G4 and fifth lens group G5, and variable aperture stop AS is arranged imagewise of location Q. This configuration minimizes the difference in vignetting over the entire surface of exposure field EF (FIG. 1) on workpiece (wafer) W.

Projection optical system 20 further comprises an aspherical surface ASP1 located in fourth lens group G4, an aspherical surface ASP2 arranged between aspherical surface ASP1 and aperture stop AS, and an aspherical surface ASP3 arranged in fifth lens group G5 imagewise of aperture stop AS.

TABLE 1A - DESIGN SPECIFICATIONS FOR WORKING EXAMPLE 1

D0 = 56.938 WD = 8.558 $ \beta  = 1/4$ Maximum NA = 0.8 $d_{EX} = 26.4$ L = 1189.996				
S	r	d	n	
1	-255.627	13.000	1.50839	



[illegible]

5	2	306.419	8.567	1	
	3	1565.905	26.363	1.50839	
	4	-286.322	1.000	1	
	5	828.381	24.476	1.50839	
	6	-314.474	1.000	1	
10	7	332.392	29.451	1.50839	
	8	-407.364	1.000	1	
	9	271.626	17.000	1.50839	
	10	204.642	6.844	1	
	11	311.458	31.538	1.50839	
15	12	-295.797	1.000	1	
	13	-2000.000	12.436	1.50839	
	14	152.723	25.832	1	
	15	-224.897	12.000	1.50839	
	16	194.016	23.075	1	
20	17	-228.159	12.500	1.50839	
	18	750.000	29.560	1	
	19	-125.249	18.000	1.50839	
	20	-456.292	6.197	1	
	21	-316.444	29.551	1.50839	
25	22	-168.563	1.000	1	
	23	$\infty$	40.572	1.50839	
	24	-267.422	1.000	1	
	25	2178.298	44.226	1.50839	
	26	-317.500	1.000	1	
	27	309.182	47.253	1.50839	
	28	-1355.659	1.000	1	
	29	171.033	46.299	1.50839	

5	30	475.084	20.092	1	
	31	465.958	20.807	1.50839	
	32	118.116	46.763	1	
	33	-211.023	12.000	1.50839	(ASP1)
	34	186.008	44.783	1	
10	35	-120.544	12.850	1.50839	
	36	$\infty$	11.955	1	
	37	-477.419	39.938	1.50839	(ASP2)
	38	-169.642	4.108	1	
	39	$\infty$	8.892	1	(Q)
15	40	684.757	40.830	1.50839	
	41	-391.691	0.000	1	
	42	$\infty$	9.043	1	(AS)
	43	1500.000	49.893	1.50839	
	44	-274.486	12.401	1	
20	45	-214.316	27.250	1.50839	
	46	-282.306	10.000	1	
	47	260.941	40.402	1.50839	
	48	1227.057	1.000	1	
	49	188.000	39.918	1.50839	
25	50	444.771	1.000	1	
	51	178.000	29.205	1.50839	
	52	308.876	1.000	1	
	53	149.162	33.190	1.50839	
	54	476.624	3.871	1	(ASP3)
	55	613.189	24.077	1.50839	
	56	65.511	6.493	1	
	57	66.070	60.000	1.50839	

58	367.843	(WD)	1	
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TABLE 1B: VALUES OF ASPHERICAL COEFFICIENTS

5	<b>Surface ASP1</b>			
	$c = -4.73883E-04$			
	$\kappa = 1.212633$			
10	$A = -1.37869E-08$			
	$B = 3.11693E-12$			
	$C = 5.04656E-17$			
15	$D = 6.46573E-22$			
	$E = -3.20804E-25$			
	$F = 1.66371E-29$			
20	<b>Surface ASP2</b>			
	$c = 2.09459E-03$			
	$\kappa = -0.419761$			
25	$A = -3.03031E-09$			
	$B = -3.82761E-13$			
	$C = 4.92647E-18$			
30	$D = -1.27524E-21$			
	$E = 1.11209E-25$			
	$F = -4.75978E-30$			
35	<b>Surface ASP3</b>			
	$c = 2.09809E-03$			
	$\kappa = 0$			
	$A = 6.78816E-09$			
	$B = 9.68697E-13$			
	$C = -5.23581E-17$			
	$D = 1.18829E-21$			
	$E = 0$			

$$F = 0$$

TABLE 1C: PARAMETERS AND DESIGN CONDITION VALUES

(1)	$0.084 \leq d_Q / \{L \times (1 - NA)\} \leq 0.209$
(2)	$f1/L = 0.125$
(3)	$-f2/L = 0.046$
(4)	$f3/L = 0.102$
(5)	$-f4/L = 0.079$
(6)	$f5/L = 0.109$
	$f1 = 148.730$
	$f2 = -54.952$
	$f3 = 120.942$
	$f4 = -93.589$
	$f5 = 129.783$
	$L = 1189.996$
	$d = 49.722$
	$NA = 0.8 \sim 0.5$

As can be seen from aberration plots 3A-3D for Working Example 1 of the present invention, distortion in particular is satisfactorily corrected over the entire large exposure region, and other aberrations are also well corrected with good balance. In addition, even though projection optical system 20 is double-telecentric with a maximum value of the  $NA = 0.8$ , the effects of vignetting are small, and the various aberrations remain satisfactorily corrected even if the  $NA$  is greatly changed. The present Working Example can be applied to a slit-like (rectangular) shape exposure field (e.g., 26mm x 8mm, or 26mm x 5mm).

#### Working Example 2

With reference to FIG. 4, projection optical system 40 represents Working Example 2 of the present invention, and has essentially the same basic configuration of lens groups as projection optical system 20 of FIG. 2, including the locations of aspherical surfaces ASP1-

APS3. Projection optical system 40 further includes an aspherical surface ASP4 arranged in first lens group G1.

TABLE 2A - DESIGN SPECIFICATIONS FOR WORKING EXAMPLE 2

D0 = 56.937 WD = 8.556 $ \beta  = 1/4$ Maximum NA = 0.8 $d_{EX} = 26.4$ L = 1190.293				
S	r	d	n	
1	-255.794	13.000	1.50839	
2	304.711	8.549	1	(ASP4)
3	1523.076	26.352	1.50839	
4	-290.961	1.000	1	
5	707.183	24.451	1.50839	
6	-337.153	1.000	1	
7	342.978	29.211	1.50839	
8	-406.487	1.000	1	
9	262.194	17.000	1.50839	
10	192.603	6.830	1	
11	282.569	31.441	1.50839	
12	-296.721	1.000	1	
13	-2000.000	12.774	1.50839	
14	156.410	25.862	1	
15	-217.396	12.000	1.50839	
16	193.187	23.071	1	
17	-229.962	12.500	1.50839	
18	753.548	29.591	1	
19	-125.018	18.000	1.50839	

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20	-470.631	6.215	1	
21	-322.848	29.532	1.50839	
22	-168.545	1.000	1	
23	$\infty$	40.488	1.50839	
24	-267.922	1.000	1	
25	2058.177	44.221	1.50839	
26	-319.862	1.000	1	
27	308.013	47.495	1.50839	
28	-1379.214	1.000	1	
29	171.065	46.313	1.50839	
30	475.356	20.101	1	
31	465.085	20.822	1.50839	
32	118.145	46.805	1	
33	-210.732	12.000	1.50839	(ASP1)
34	186.081	44.774	1	
35	-120.565	12.850	1.50839	
36	$\infty$	11.978	1	
37	-477.987	39.928	1.50839	(ASP2)
38	-169.679	4.102	1	
39	$\infty$	8.911	1	(Q)
40	682.568	40.816	1.50839	
41	-391.897	0.000	1	
42	$\infty$	9.070	1	(AS)
43	1500.000	49.868	1.50839	
44	-274.701	12.416	1	
45	-214.373	27.250	1.50839	
46	-282.422	10.000	1	
47	260.913	40.405	1.50839	

48	1226.772	1.000	1	
49	188.000	39.907	1.50839	
50	444.503	1.000	1	
51	178.000	29.185	1.50839	
52	308.504	1.000	1	
53	149.159	33.191	1.50839	
54	474.418	3.897	1	(ASP3)
55	612.596	24.177	1.50839	
56	65.478	6.451	1	
57	66.000	60.000	1.50839	
58	368.643	(WD)	1	

TABLE 2B: VALUES OF ASPHERICAL COEFFICIENTS

Surface ASP1
$c = -4.74536E-03$
$\kappa = 1.223505$
$A = -1.41105E-08$
$B = 3.15056E-12$
$C = 5.33738E-17$
$D = 6.14925E-22$
$E = -3.11253E-25$
$F = 1.59082E-29$
Surface ASP2
$c = -2.09211E-03$
$\kappa = -0.445417$
$A = -2.99871E-09$
$B = -3.87784E-13$
$C = 4.85381E-18$
$D = -1.27131E-21$

	$E = 1.09975E-25$
	$F = -4.70926E-30$
5	<b>Surface ASP3</b>
	$c = 2.10785E-03$
	$\kappa = 0$
	$A = 6.70585E-09$
	$B = 9.66412E-13$
10	$C = -5.16458E-17$
	$D = 1.16221E-21$
	$E = 0$
	$F = 0$
15	<b>Surface ASP4</b>
	$c = 3.28179E-03$
	$\kappa = 0$
	$A = -3.81013E-09$
20	$B = 2.15522E-13$
	$C = 7.31492E-18$
	$D = -1.31012E-21$
	$E = 0$
	$F = 0$

	<b>TABLE 2C: PARAMETERS AND DESIGN CONDITION VALUES</b>
	(1) $0.084 \leq d_Q/\{L \times (1-NA)\} \leq 0.209$
30	(2) $f1/L = 0.125$
	(3) $-f2/L = 0.046$
	(4) $f3/L = 0.101$
	(5) $-f4/L = 0.079$
	(6) $f5/L = 0.109$



	$f1 = 148.873$
	$f2 = -54.783$
	$f3 = 120.796$
5	$f4 = -93.618$
	$f5 = 129.808$
	$L = 1190.293$
	$d = 49.726$
	$NA = 0.8 \sim 0.5$

As can be seen from aberration plots 5A-5D for Working Example 2 of the present invention, distortion in particular is satisfactorily corrected over the entire large exposure region, and other aberrations are also well corrected with good balance. In addition, even though projection optical system 40 is double-telecentric with a maximum value of the  $NA = 0.8$ , the effects of vignetting are small, and the various aberrations remain satisfactorily corrected even if the  $NA$  is greatly changed. The present Working Example can be applied to a slit-like (rectangular) shape exposure field (e.g., 26m x 8 mm or 26mm x 5mm).

### Working Example 3

With reference to FIG. 6, projection optical system 60 represents Working Example 3 of the present invention, and has essentially the same basic configuration of lens groups as projection optical system 20 of FIG. 2, including the locations of aspherical surfaces ASP1-APS3. Projection optical system 60 further includes an aspherical surface ASP5 is arranged in second lens group G1.

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TABLE 3A - DESIGN SPECIFICATIONS FOR WORKING EXAMPLE 3

D0 = 56.947  
WD = 7.678  
 $|\beta| = 1/4$   
Maximum NA = 0.8  
 $d_{EX} = 26.4$   
L = 1191.307

S	r	d	n	
1	-295.194	13.000	1.50839	
2	307.090	11.543	1	
3	2094.974	20.585	1.50839	
4	-308.498	1.000	1	
5	798.586	25.527	1.50839	
6	-348.935	1.000	1	
7	421.955	28.789	1.50839	
8	-335.489	1.000	1	
9	281.085	17.000	1.50839	
10	210.236	3.852	1	
11	248.819	31.665	1.50839	
12	-312.999	1.000	1	
13	-2000.000	12.729	1.50839	
14	150.843	27.217	1	
15	-203.928	12.000	1.50839	
16	167.173	26.604	1	
17	-208.236	12.500	1.50839	
18	957.666	24.946	1	(ASP5)
19	-147.060	18.000	1.50839	
20	-378.007	7.483	1	
21	-258.912	25.237	1.50839	
22	-168.885	1.000	1	

[illegible]

23	$\infty$	40.270	1.50839	
24	-266.905	1.000	1	
25	1909.000	44.411	1.50839	
26	-318.771	1.000	1	
27	281.823	48.046	1.50839	
28	-2703.904	1.000	1	
29	173.110	46.118	1.50839	
30	491.765	23.296	1	
31	475.493	20.366	1.50839	
32	120.322	46.663	1	
33	-209.981	12.000	1.50839	(ASP1)
34	197.000	45.464	1	
35	-114.299	12.850	1.50839	
36	-5000.000	11.908	1	
37	-478.278	42.997	1.50839	(ASP2)
38	-169.870	4.260	1	
39	$\infty$	8.837	1	(Q)
40	683.041	40.543	1.50839	
41	-386.391	0.000	1	
42	$\infty$	8.716	1	(AS)
43	1378.469	47.021	1.50839	
44	-287.893	17.279	1	
45	-214.067	27.250	1.50839	
46	-277.449	10.000	1	
47	260.145	42.695	1.50839	
48	1760.879	1.000	1	
49	189.250	38.807	1.50839	
50	444.163	1.000	1	

51	180.000	27.895	1.50839	
52	297.607	1.000	1	
53	155.389	32.579	1.50839	
54	496.127	4.141	1	(ASP3)
55	712.002	27.982	1.50839	
56	65.481	4.652	1	
57	66.000	59.959	1.50839	
58	441.381	(WD)	1	

TABLE 3B: VALUES OF ASPHERICAL COEFFICIENTS

**Surface ASP1**

$$c = -4.76234E-03$$

$$\kappa = 0.861651$$

$$A = -7.84820E-09$$

$$B = 3.01423E-12$$

$$C = 9.70754E-17$$

$$D = 1.62617E-21$$

$$E = -2.56672E-25$$

$$F = 1.42087E-29$$

**Surface ASP2**

$$c = -2.09084E-03$$

$$\kappa = 2.804972$$

$$A = -8.77018E-09$$

$$B = -4.80478E-13$$

$$C = -3.02578E-18$$

$$D = -2.74308E-21$$

$$E = 2.11317E-25$$

$$F = -1.37915E-29$$

[illegible]

Surface ASP3
$c = 2.01561\text{E-}03$
$\kappa = 0$
$A = 5.23214\text{E-}10$
$B = 1.19414\text{E-}12$
$C = -5.86228\text{E-}17$
$D = 1.24893\text{E-}21$
$E = 0$
$F = 0$
Surface ASP5
$c = 1.04421\text{E-}03$
$\kappa = 0$
$A = -2.65532\text{E-}08$
$B = -4.16828\text{E-}13$
$C = 5.01741\text{E-}18$
$D = -6.52068\text{E-}21$
$E = 7.82794\text{E-}25$
$F = -6.18178\text{E-}29$

TABLE 3C: PARAMETERS AND DESIGN CONDITION VALUES	
(1)	$0.083 \leq d_Q/\{L \times (1-NA)\} \leq 0.207$
(2)	$f1/L = 0.123$
(3)	$-f2/L = 0.047$
(4)	$f3/L = 0.104$
(5)	$-f4/L = 0.080$
(6)	$f5/L = 0.110$
	$f1 = 145.982$
	$f2 = -56.252$
	$f3 = 123.837$

	$f4 = -94.933$
	$f5 = 131.432$
	$L = 1191.307$
	$d = 49.380$
5	$NA = 0.8 \sim 0.5$

As can be seen from aberration plots 7A-7D for Working Example 3 of the present invention, distortion in particular is satisfactorily corrected over the entire large exposure region, and other aberrations are also well corrected with good balance. In addition, even though projection optical system 60 is double-telecentric with a maximum value of the  $NA = 0.8$ , the effects of vignetting are small, and the various aberrations remain satisfactorily corrected even if the  $NA$  is greatly changed. The present Working Example can be applied to a slit-like (rectangular) shape exposure field (e.g., 26mm x 8mm or 26mm x 5mm).

#### Working Example 4

With reference to FIG. 8, projection optical system 80 represents Working Example 4 of the present invention, and has essentially the same basic configuration of lens groups as projection optical system 20 of FIG. 2, including the locations of aspherical surfaces ASP1-APS3. Projection optical system 60 further includes an aspherical surface ASP6 is arranged in third lens group G1.

TABLE 4A - DESIGN SPECIFICATIONS FOR WORKING EXAMPLE 4

	$D0 = 56.195$ $WD = 8.547$ $ \beta  = 1/4$ Maximum $NA = 0.8$ $d_{EX} = 26.4$ $L = 1189.851$			
	S	r	d	n
	1	-281.019	13.000	1.50839
	2	316.929	8.609	1
	3	2500.000	26.225	1.50839

[illegible]

5	4	-303.360	1.000	1	
	5	804.062	24.227	1.50839	
	6	-318.842	1.000	1	
	7	354.459	29.152	1.50839	
	8	-377.293	1.000	1	
10	9	263.543	17.000	1.50839	
	10	199.659	6.604	1	
	11	295.344	30.241	1.50839	
	12	-307.153	1.074	1	
	13	-2000.000	13.052	1.50839	
15	14	152.095	25.535	1	
	15	-226.948	12.000	1.50839	
	16	199.970	23.919	1	
	17	-200.430	12.500	1.50839	
	18	750.000	29.580	1	
20	19	-134.929	18.000	1.50839	
	20	-423.324	6.957	1	
	21	-286.676	29.399	1.50839	
	22	-167.682	1.000	1	
	23	$\infty$	40.813	1.50839	
25	24	-266.938	1.000	1	
	25	3220.051	42.890	1.50839	
	26	-317.569	1.000	1	
	27	302.026	48.170	1.50839	
	28	-1518.815	1.000	1	(ASP6)
	29	171.737	46.214	1.50839	
	30	481.358	20.022	1	
	31	458.364	20.729	1.50839	

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085	2086	2087	2088	2089	2090	2091	2092	2093	2094	2095	2096	2097	2098	2099	2100	2101	2102	2103	2104	2105	2106	2107	2108	2109	2110	2111	2112	2113	2114	2115	2116	2117	2118	2119	2120	2121	2122	2123	2124	2125	2126	2127	2128	2129	2130	2131	2132	2133	2134	2135	2136	2137	2138	2139	2140	2141	2142	2143	2144	2145	2146	2147	2148	2149	2150	2151	2152	2153	2154	2155	2156	2157	2158	2159	2160	2161	2162	2163	2164	2165	2166	2167	2168	2169	2170	2171	2172	2173	2174	2175	2176	2177	2178	2179	2180	2181	2182	2183	2184	2185	2186	2187	2188	2189	2190	2191	2192	2193	2194	2195	2196	2197	2198	2199	2200	2201	2202	2203	2204	2205	2206	2207	2208	2209	2210	2211	2212	2213	2214	2215	2216	2217	2218	2219	2220	2221	2222	2223	2224	2225	2226	2227	2228	2229	2230	2231	2232	2233	2234	2235	2236	2237	2238	2239	2240	2241	2242	2243	2244	2245	2246	2247	2248	2249	2250	2251	2252	2253	2254	2255	2256	2257	2258	2259	2260	2261	2262	2263	2264	2265	2266	2267	2268	2269	2270	2271	2272	2273	2274	2275	2276	2277	2278	2279	2280	2281	2282	2283	2284	2285	2286	2287	2288	2289	2290	2291	2292	2293	2294	2295	2296	2297	2298	2299	2300	2301	2302	2303	2304	2305	2306	2307	2308	2309	2310	2311	2312	2313	2314	2315	2316	2317	2318	2319	2320	2321	2322	2323	2324	2325	2326	2327	2328	2329	2330	2331	2332	2333	2334	2335	2336	2337	2338	2339	2340	2341	2342	2343	2344	2345	2346	2347	2348	2349	2350	2351	2352	2353	2354	2355	2356	2357	2358	2359	2360	2361	2362	2363	2364	2365	2366	2367	2368	2369	2370	2371	2372	2373	2374	2375	2376	2377	2378	2379	2380	2381	2382	2383	2384	2385	2386	2387	2388	2389	2390	2391	2392	2393	2394	2395	2396	2397	2398	2399	2400	2401	2402	2403	2404	2405	2406	2407	2408	2409	2410	2411	2412	2413	2414	2415	2416	2417	2418	2419	2420	2421	2422	2423	2424	2425	2426	2427	2428	2429	2430	2431	2432	2
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32	121.840	46.884	1	
33	-203.076	12.000	1.50839	(ASP1)
34	185.000	45.147	1	
35	-121.196	12.850	1.50839	
36	$\infty$	11.728	1	
37	-465.519	39.959	1.50839	(ASP2)
38	-170.031	4.118	1	
39	$\infty$	8.882	1	(Q)
40	663.260	40.673	1.50839	
41	-392.224	0.000	1	
42	$\infty$	9.244	1	(AS)
43	1492.727	49.719	1.50839	
44	-277.593	12.757	1	
45	-214.522	27.250	1.50839	
46	-282.481	10.000	1	
47	261.717	41.243	1.50839	
48	1246.120	1.000	1	
49	188.000	39.612	1.50839	
50	439.103	1.000	1	
51	178.000	29.125	1.50839	
52	307.599	1.000	1	
53	147.699	33.313	1.50839	
54	461.089	4.088	1	(ASP3)
55	612.505	24.500	1.50839	
56	65.463	6.105	1	
57	66.000	60.000	1.50839	
58	373.143	(WD)	1	



TABLE 4B: VALUES OF ASPHERICAL COEFFICIENTS

	Surface ASP1
5	$c = -4.92426E-03$
	$\kappa = 1.140743$
	$A = -1.17013E-08$
	$B = 2.95847E-12$
	$C = 7.22796E-17$
10	$D = 3.50053E-21$
	$E = -4.73158E-25$
	$F = 1.77468E-29$
15	Surface ASP2
	$c = -2.14814E-03$
	$\kappa = -0.511241$
	$A = -2.90908E-09$
	$B = -3.82923E-13$
20	$C = 9.51818E-19$
	$D = -1.02058E-21$
	$E = 7.38868E-26$
	$F = -3.11809E-30$
25	Surface ASP3
	$c = 2.16878E-03$
	$\kappa = 0$
	$A = 6.88715E-09$
30	$B = 8.36584E-13$
	$C = -4.26325E-17$
	$D = 9.02955E-22$
	$E = 0$
	$F = 0$

	<b>Surface ASP6</b>
	$c = -6.58408E-04$
5	$\kappa = 0$
	$A = -1.29700E-09$
	$B = -2.23515E-14$
	$C = 2.71217E-19$
	$D = 4.78605E-24$
10	$E = 0$
	$F = 0$

15	<b>TABLE 4C: PARAMETERS AND DESIGN CONDITION VALUES</b>
	(1) $0.084 \leq d_Q/\{L \times (1-NA)\} \leq 0.208$
	(2) $f1/L = 0.125$
	(3) $-f2/L = 0.047$
	(4) $f3/L = 0.103$
20	(5) $-f4/L = 0.079$
	(6) $f5/L = 0.109$
	$f1 = 148.857$
	$f2 = -55.987$
25	$f3 = 122.578$
	$f4 = -93.819$
	$f5 = 130.011$
	$L = 1189.851$
	$d = 49.554$
30	$NA = 0.8 \sim 0.5$

As can be seen from aberration plots 9A-9D for Working Example 4 of the present invention, distortion in particular is satisfactorily corrected over the entire large exposure region, and  
35 other aberrations are also well corrected with good balance. In addition, even though

projection optical system 60 is double-telecentric with a maximum value of the NA = 0.8, the effects of vignetting are small, and the various aberrations remain satisfactorily corrected even if the NA is greatly changed. The present Working Example can be applied to a slit-like (rectangular) shape exposure field (e.g., 26mm x 8mm or 26mm x 5mm).

5

It will be apparent to one skilled in the art that the abovementioned modes for carrying out the present invention is not limited to a particular wavelength or narrow band centered thereon. For example, the present invention can be applied to an ultraviolet wavelength of  $\lambda = 248.4$  nm (e.g., from a KrF laser), or deep ultraviolet light of  $\lambda = 193$  nm (e.g., from an ArF laser),  $\lambda = 157$  nm (e.g., from an F<sub>2</sub> laser), and  $\lambda = 147$  nm (e.g., from a Kr<sub>2</sub> laser). In addition, the present invention can be applied to other wavelengths in the ultraviolet region like the g-line ( $\lambda = 435.8$  nm wavelength) and i-line ( $\lambda = 365.0$  nm wavelength) of mercury lamps, the higher harmonics of YAG lasers (e.g.,  $\lambda = 248$ nm, 193nm, or 157nm) and the like. In addition, other glass types besides quartz, such as fluorite (calcium fluoride, CaF<sub>2</sub>), barium fluoride (BaF<sub>2</sub>), lithium fluoride (LiF) and magnesium fluoride (MgF<sub>2</sub>) can also be used. The embodiments of the present invention were described above in connection with step-and-scan projection exposure apparatus. However, the projection optical system of present invention can be applied to step-and-repeat projection exposure apparatus as well. In this case, the exposure field can use, e.g., a square shape, or rectangular shape inside a circular area of diameter 26.4mm. In addition, though the projection magnification (lateral magnification) of the above embodiments and Working Examples is a reduction magnification, the present invention can be applied to unit magnification, or enlargement magnification.

## 25 **Semiconductor Device Manufacturing Method**

The present invention includes a method of patterning a workpiece using exposure apparatus 10 of FIG. 1. The method includes the steps of providing a layer of photosensitive material onto workpiece (wafer) W, projecting an image of the pattern of object (reticle) R through projection optical system PL onto workpiece (wafer) W, and developing the photosensitive material on workpiece (wafer) W. An additional step of forming a predetermined circuit pattern on workpiece (wafer) W (e.g., via an etch process) using the

post-developed photosensitive material as the mask may also be performed. Such a method results in a high-resolution device circuit pattern on workpiece (wafer) W formed substantially without image distortion.

- 5 With reference now also to FIG. 10 and flow chart 100, a method of manufacturing a semiconductor device is now explained. First, in step 1, a metal film is vapor deposited on each wafer in a "lot" (i.e., group) of wafers. In step 2, photoresist is coated on the metal film on each wafer in the lot. Subsequently, in step 3, using projection exposure apparatus 10 of FIG. 1 provided with a projection optical system PL according to the present invention as described above, the image of the pattern (not shown) on object (reticle) R is sequentially exposed and transferred to one or more exposure fields EF on each wafer W in the lot of wafers, through projection optical system PL. Then, in step 4, the photoresist on each wafer in the lot of wafers is developed. Next, in step 5, by etching each wafer W in the lot of wafers using the developed photoresist as the mask, a circuit pattern corresponding to the pattern on reticle R is formed in each exposure field EF on each wafer W in the lot of wafers. Subsequently, in step 6, by further forming additional circuit patterns (e.g., upper-layer circuit patterns) using the next process, semiconductor devices are manufactured.

- 20 Since projection optical system PL in the present example is double-telecentric and its NA is large and variable, fine circuit patterns can be stably formed with high resolution on each wafer W, even if there is warpage in reticle R or warpage in each wafer to be exposed. In addition, since exposure region EF of projection optical system PL is large, large devices can be manufactured with high throughput.

- 25 Furthermore, it will be understood the present invention is not limited to the abovementioned modes and Working Examples for carrying out the present invention and, within a range that does not deviate from the purport of the present invention, a variety of configurations are obtainable.